

Establishment of a Mars Climate Modeling Center (MCMC)
for the
National Aeronautics and Space Administration

A White Paper

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Executive Summary

This White Paper submitted to the Planetary Science Division of NASA Headquarters, is a result of an exploratory workshop that was held at the NASA Ames Research Center, Space Science and Astrobiology Division, 30 September to 2 October 2008 (<http://mcmcworkshop.arc.nasa.gov>). The purpose of this two-and-a-half day workshop was to discuss with members of the Agency and the scientific and engineering communities the needs for, the basic charter of, and the guidelines on, the establishment of a centralized Mars Climate Modeling Center (MCMC) as an Agency asset with regards to its Mars Exploration Program (MEP), in addition to a community resource with regards to Mars atmospheric and climate research.

The MCMC Mission

To provide a Mars atmospheric science and global climate modeling resource for the Nation's Mars Exploration Program

To foster community interaction and access on endeavors related to Mars atmospheric science and climate research

To understand the structure and variability of Mars' atmosphere and climate on the basis of physical systems and processes

To promote the exchange of atmospheric and climate science knowledge related to the exploration of Mars

In the first section, a summary of the MCMC workshop is presented. This includes a description of elements of the basic charter and key concerns that were raised by the community during the autumn 2008 workshop.

The second section discusses the rationale for establishing a centralized facility dedicated to Mars climate modeling for the Agency and the community, and reasons it should be established at the NASA Ames Research Center. Relevant Mars Exploration goals as mentioned in recent decadal surveys are briefly mentioned.

The third section lists the fundamental elements of the MCMC charter. All components of this charter have at their foundation mission support and community service.

The fourth section describes in detail the functions and activities that will be carried out at the MCMC. These activities are all linked to the elements of the MCMC charter.

The fifth section presents the organizational structure of the proposed MCMC. The organizational structure consists of three basic tiers that are streamlined. All three tiers would offer guidance on MCMC operations. In addition, the initial staffing requirements of the MCMC are presented.

The sixth section discusses high-end computing (HEC) assets collocated at NASA Ames, and their utility and application to the MCMC.

The seventh section presents the importance of community interactions with the MCMC. Through the integration of such external inputs, the MCMC would be enhanced for the Agency and the community.

The eighth section discusses methods of reviews and accountability for the MCMC.

Appendix A gives the final agenda of the MCMC workshop. Also listed in this appendix is full contact information for all registered participants.

1.0 MCMC Workshop at NASA Ames

Supported by the Planetary Science Division of NASA Headquarters, an exploratory workshop on the establishment of a Mars Climate Modeling Center (MCMC) was convened at the NASA Ames Research Center (ARC), Space Science and Astrobiology Division, 30 September to 2 October 2008 (<http://mcmcworkshop.arc.nasa.gov>). Approximately 60 attendees participated, consisting of a large cross section of the Mars atmospheric and climate, and mission engineering and support communities. Participants came from scientific and engineering groups within academia; non- and for-profit research institutes; NASA Headquarters and five NASA centers; and, other government research labs. In addition, staff from one of the Agency's high-end computing (HEC) assets, the NASA Advanced Computing Division (NAS) facility located at ARC, participated in the workshop.

The primary purpose of the workshop was to discuss the needs of the Agency and the community for a dedicated center for Mars climate modeling to support the Mars Exploration Program (MEP) and future mission planning activities. Furthermore, the MCMC would become a bona fide and "user-friendly" resource for the Mars climate research community.

Community consensus was reached with regards to the fundamental charter of the MCMC. The fundamental charter consists of the following key elements: (i) develop and continuously improve a state-of-the-art Mars general circulation model (GCM); (ii) support NASA missions to Mars; (iii) provide a framework for community access to the center and all of its components; and, (iv) create and maintain a *Mars Climate Database (MCD)*. Participants of the community also raised the following key points that need to be kept in mind related to the MCMC charter:

- Start *simple* and emphasize *community service* across all components of the MCMC that support NASA research directed at Mars and future mission-related planning and engineering studies
- Limit and constrain scientific research performed at the MCMC to those projects that will fundamentally improve the modeling capability of the climate center (e.g., development of future physical parameterizations)

The MCMC workshop's agenda and a list of participants are given in Appendix A.

2.0 MCMC Rationale

Within the US space program, Mars continues to be an object of considerable interest and study as thoroughly discussed in recent National Research Council decadal surveys and related reports (NRC 2006a; 2006b). A continued campaign of investigations is emphasized by the Mars Exploration Program Advisory Group (MEPAG, 2006; 2008). In particular, Goals II and IV of the latter reports seek to answer basic questions related to Mars' present and past climates, and thoroughly characterize the planetary environment related to human exploration. With fundamental questions related to the study of life (extant and/or in past epochs), and in more generalized astrobiology contexts, Mars continues to be *the* neighboring world of tremendous potential. Increasingly accurate numerical modeling and analysis of the structure and variability of the near-surface and upper atmosphere will be needed to support the next generation of Mars missions. Full characterization of the atmosphere is vital to support future aerocapture/aerobraking and entry, decent and landing (EDL) activities, and is paramount for atmospheric hazard mitigation as well as the ultimate success of such missions. Further, it is critical to the development of new instruments as well as for an assessment of their environmental performance.

Establishing a dedicated, centralized facility for Mars climate modeling and atmospheric science for the Agency and further, for the community, is critical to a comprehensive exploration program of Mars, particularly with regards to long-range goals of human exploration of the planet (NRC 2006a; 2006b). Formulating an understanding of the structure and variability of the planet's atmospheric environment is key to ongoing – and critical in the design of future-planned – spacecraft missions to Mars, particularly the more fully autonomous ones targeted at the planet's surface and with respect to missions dedicated to Mars Sample Return (MSR).

Because of such needs of the Agency and its Mars Exploration Program — from a mission standpoint as well as service to the Mars climate community — having a centralized, state-of-the-art climate modeling capability that is steadfast with directed support is crucial in order to meet the exploration goals. Deriving such supports entirely through NASA's research and analysis (R&A) programs is not the appropriate venue, because R&A is fundamentally science driven and mission support or community service is not guaranteed. Within a centralized facility, the capability to deliver on increasing demands for service-related activities will occur at a much higher efficiency. And, just as it is for the case of Earth climate science, a core capacity for Mars climate science that is centralized, adequately funded and staffed, and that has longevity and resilience is paramount to growth and development related to new climate modeling techniques and parameterizations of physical processes (Arakawa, 2000; NRC 2001).

There are many reasons for establishing the MCMC at the NASA Ames Research Center (ARC). First, because ARC is one of the Agency's centers, NASA has direct control. Other institutions (e.g., universities and non-profit organizations) operate independently and may not always have NASA's best interests in mind. ARC is unencumbered by potential conflicts unrelated to the core mission (e.g., for profit or award of research dollars).

Second, over the past 35 years, the Mars general circulation modeling (Mars GCM) project based at ARC has been the "go to" center for Mars atmospheric and climate science (both present and past climates), has a proven track record in developing Mars GCMs, and has unmatched knowledge, experience and intellectual capital. ARC has also cultivated extensive collaborations and partnerships worldwide, which facilitates more rapid and sophisticated model development through an open exchange of ideas with other premier domestic and foreign modeling groups. This effort has a long-standing funding history via various NASA ROSES program elements.

Third, ARC and the Mars GCM effort has supported nearly every mission to Mars since the *Viking* mission. This support has been in the form of near-surface environment characterization (e.g., seasonal and geographical variations in winds, temperature, dust loading, net incoming solar radiation, etc); atmospheric assessment and characterization for entry, decent and landing (EDL); and, upper atmosphere structure determinations (e.g., mean density and expected variability) that can influence both atmospheric aerobraking and aerocapture. The ARC Mars GCM project continues to be utilized in various engineering and concept studies for future Mars missions.

And fourth, there is unprecedented synergy with one of NASA's High-End Computing (HEC) assets which resides at ARC, the NASA Advanced Supercomputing (NAS) facility. Within the proposed MCMC, this facility will be utilized locally and remotely by the broader community for climate simulations, data analysis and visualization, in addition to data archiving.

3.0 MCMC Charter

The fundamental charter of the MCMC would be based on the following four core elements:

Develop and continuously improve a state-of-the-art Mars GCM
Support NASA Mars missions
Engage the community by providing a framework for community access to the model and full documentation
Generate and maintain a <i>Mars Climate Database (MCD)</i>

In one form or another, each of these charter elements have already been partially supported by ARC through its Mars GCM effort. The MCMC would provide a formal framework to ensure that these activities continue to be accomplished.

The governing principals for a MCMC are to support the Agency's mission needs, to make the most of both current and future mission data, to improve modeling fidelity, to promote community access, and to facilitate future NASA plans for Mars both robotically and for human exploration purposes. Broad community participation is desirable and will be encouraged so that the whole activity shall benefit from all scientists who can contribute to this center and stimulate, foster, and enhance knowledge and cooperation in Mars global climate research.

In addition, the MCMC needs to be established in a flexible way so that it can evolve to meet new requirements of the Agency MEP and new needs of the Mars climate community.

Just as it is in the Earth GCM community, it must emphasized that the MCMC model will not be the *only* Mars GCM (or even regional-scale model) supported by NASA's PSD. There is great value in having more than one large-scale atmospheric model for the community. Fundamentally, the effort at Ames will be to build on results and lessons learned of other ongoing modeling efforts to

provide a standardized, state-of-the-art model for community use and MEP support.

4.0 MCMC Functions and Activities

The essential functions and activities of the MCMC are described below. These activities originate from a larger list that was presented during the MCMC workshop. After open discussions amongst the workshop participants and consensus was reached, the following key functions were identified. They are fundamentally linked to the basic charter of the MCMC.

Create a State-of-the-art Mars Climate Model

An essential function of the MCMC is to create a state-of-the-art Mars climate model that is an asset for the Agency and also for the entire Mars climate community. This asset should be sufficiently supported such that within the MCMC, the climate model would be fully tested and debugged, documented and maintained. A fully functional state-of-the-art climate model is requisite for testing, debugging and assessing the effects of newly-developed physics packages and parameterizations at the MCMC on the nature of the simulated climate.

The MCMC will begin by adapting the National Oceanic and Atmospheric Administration's (NOAA), Geophysical Fluid Dynamics Laboratory (GFDL) so-called "Flexible Modeling System" (FMS) as a climate modeling framework (<http://www.gfdl.noaa.gov/~fms>). The FMS is widely flexible in that a variety of physics packages can easily be assembled and then coupled to the dynamical processor to build up a complete modeling system. This modernized framework includes well-tested, state-of-the-art dynamical processors based on finite-volume methods for solving the governing prognostic equations of meteorology. Because of their global conservation attributes regarding scalar/vector fields, finite volume methods are becoming a standard in climate modeling. Another advantage of these recent dynamical solvers is the capability to make use of non-standard grid geometries (e.g., a "cubed-sphere" approach that has highly-resolved separate 2D computational "tiles"). This geometry removes the classic pole problem accompanying latitude-longitude grid-point models wherein spectral filtering/truncation in middle/high latitudes is necessary for computational stability. An example of the cube-sphere computational grid is shown in Figure 1. This method will be far superior in simulating atmospheric processes in the polar region, such as, the sublimation of water from Mars' north residual cap.

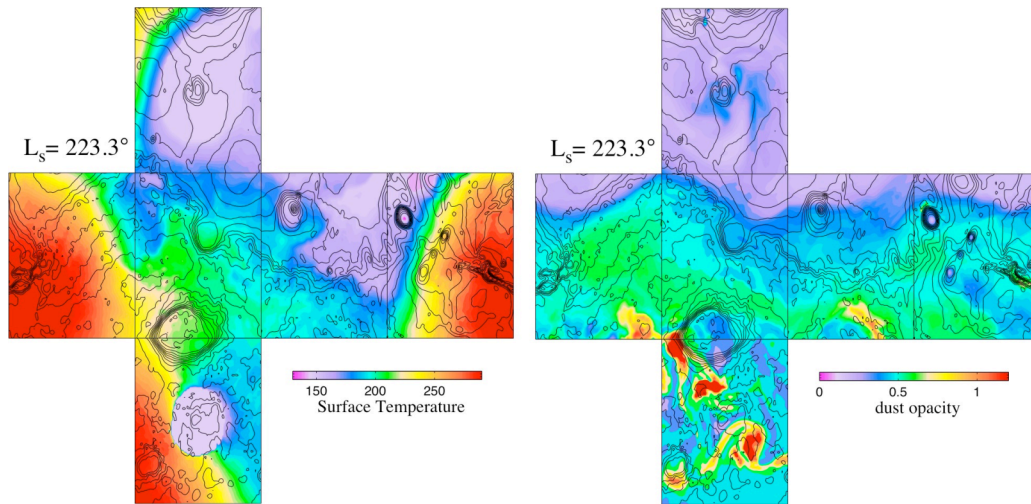


Figure 1: FMS cubed-sphere Mars GCM simulation showing surface temperature and dust opacity during late northern fall.

The MCMC will adapt Mars-specific physical parameterizations developed and tested at NASA Ames and insert these into the FMS to create a fully-functional, modern and generalized Mars climate modeling capability for the Agency and the Mars climate community, with all the requisite support infrastructure and documentation. Development and testing of a generalized radiation physics package is an enormous task and takes considerable resources. For several years, NASA Ames has been working on such a package with a modular design and with complete documentation. Together with upgrades, Ames has continuously made versions available to the community at large, and will continue in this endeavor.

The ultimate goal is to permit users to literally pick and choose as they wish to assemble a Mars climate model for a particular application or research problem. However, in addition to this “plug-and-play” approach, fully ready Mars GCMs will be made available which would have various degrees of sophistication and include a spectrum of physical parameterizations.

Standardized practices for climate model outputs will be implemented (e.g., netCDF files for “raw” model output and run-time statistics). In addition, a suite of climate diagnostic tools will be developed, tested and made available with full documentation which will permit users to efficiently and easily assess the climate simulations that they perform. Visualization tools will also similarly be made available and supported. At the Ames NAS facility, high performance visualization methods is an area of considerable expertise and this will be leveraged within the MCMC.

Simulations performed with the state-of-the-art climate model will be compared and contrasted with available spacecraft observations of Mars' atmosphere (e.g. those available from recent missions such as Mars Global Surveyor, Mars Odyssey, Mars Express and Mars Reconnaissance Orbiter). In this light, the climate simulations will be "validated" against the best atmospheric measurements to date. Finally, such climate simulations and data comparisons will be documented as MCMC Technical Notes as well as published in the scientific literature.

Continuously Improve the Model

Driven by comparison with past and more importantly new atmospheric observations, the state-of-the-art model supported by and maintained at the MCMC will continuously be updated through the development of new physical parameterizations specific to Mars' climate system. This is similar to how advancements are made in Earth climate modeling community capabilities, as well as in the improvement of in climate model biases. Both in-house developments and those provided by the community will be utilized. For all improvements, coding standards will be adhered to and careful benchmarking will be undertaken. Again, the MCMC will work in house as well as solicit inputs (e.g., via hosting workshops; assisting in the porting of codes; etc) from the entire community in these endeavors. The results of such improvements will also be documented in Technical Notes as well as in the scientific literature. In this way, the model resources within the MCMC will remain vibrant and at the cutting edge and become a shared, common community investment.

Manage the Source Code

Another key function of the MCMC is to develop, fully test and debug, clearly document, and continually maintain and archive (until code obsolescence) all source code and modules that reside in the MCMC code repository. All code must become highly modernized using a common framework that is flexible, modular and efficient so that full models and model components are interoperable and portable to a range of computer architectures (e.g., massively parallel machines; multi- and single-processor workstations; etc). Such common modeling infrastructure (CMI) practices are necessary ingredients for improving the effectiveness and efficiency of global climate modeling for the Earth (NRC 2001), and will improve the effectiveness related to planetary atmospheres and their climates. Toward this end, utilization of standard source code control system software will be necessary. For example, an open-source standard is the so-called Concurrent Versions System (CVS), which is freely available and widely

used by many code developers. The proposed FMS framework is based upon and leverages such a CMI approach.

Generate a Mars Climate Database

A fundamental function of the MCMC, and one that has considerable community appeal, is the creation of a “user-friendly” *Mars Climate Database* (MCD) that can be easily accessed through the web. An example of such a database is that maintained in Paris, France based at the Laboratoire de Météorologie Dynamique du CNRS (LMD) (<http://johnson.lmd.jussieu.fr:8080/las/servlets/dataset>). This database is based on statistics describing the climate and environment of the Martian atmosphere constructed from output from multi-annual integrations of a Mars GCM developed by LMD, in collaboration with various European institutions, with support from the European Space Agency (ESA) and Centre National d'Etudes Spatiales (CNES).

The MCMC will develop a domestic variation of such a MCD. Again, the plan is start simple yet at the same time be adaptive to the needs of the science and engineering communities for environmental databases related to the Mars climate system. Key ingredients of these databases will include global assessments of temperatures, density, pressure and winds (both means and their variability) for a variety of atmospheric dust-loading scenarios. In addition, easy-to-use software tools that can efficiently access the database for processing and visualization will be required. Along with the MCD, relevant atmospheric observational data (e.g., temperature and pressure profiles) in standard form will also be an archived component in an easily-accessible data repository local to the MCMC so that quick comparisons with the climate simulations and statistics can be made.

Provide Community Access

A key ingredient of a successful MCMC will be open access to all and broad community participation. Toward this end, a dedicated, fully-functional and friendly web site will be established. This web site will not only be the portal for model codes, full documentation, user guides, sample run scripts, post-processing tools, standard climate-run experiments, but also, MCMC highlights, MCMC news and events, Technical Notes, publications, and other relevant information.

The MCMC will hold training and instructional sessions for users, be they expert users, engineering users, and/or non-expert or non-engineering users. In addition, the MCMC will host special-focus workshops for the community.

Examples of such focused workshops might be on the application of new physical parameterizations, new analysis and diagnostic techniques, or specific climate processes (e.g., physical processes relevant to Mars' dust cycle). These workshops and training sessions would also offer a forum for obtaining community needs and inputs.

5.0 Organizational Structure

A proposed organizational structure of the MCMC is depicted in the following diagram (Figure 2) and consists of three basic tiers. At the center tier are the science and engineering communities, the MCMC Director, and a Steering Committee. Underneath this tier are the core staff of the MCMC. Above the center tier are NASA Headquarters and an independent Advisory Board. These components are briefly described below.

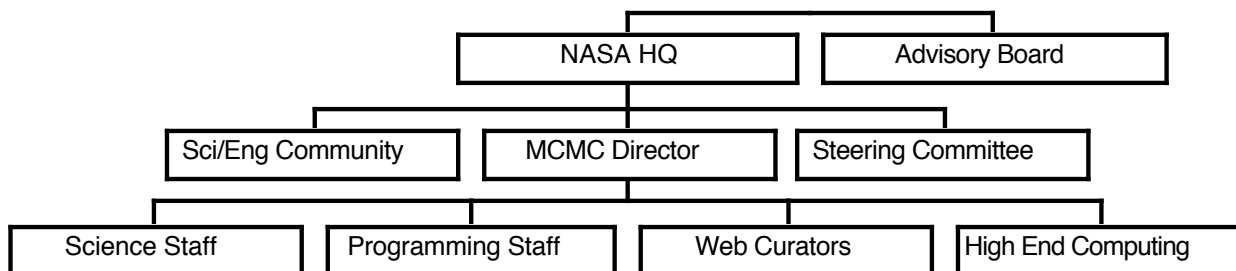


Figure 2: A three-tiered organizational structure of the MCMC: (a) NASA HQ and Advisory Board; (b) MCMC Director, Steering Committee and the Community; and (c) MCMC core staff.

A realistic MCMC requires adequate core staffing that is centrally located at the modeling center. Given the elements of the charter listed in section 3, and the functions and activities listed in section 4, together with the recommendation that the MCMC begin simple, we estimate that the *initial* staffing would include: Mars climate and atmospheric scientists (4 FTE); dedicated computer programmers (2 FTE); a web curator (1 FTE); and an administrative assistant to help with meetings, travel, workshops, etc (0.5 FTE). In addition to this centralized staff, some distant/remote "staff" may also be supported on a part-time basis. Also required is a separate dedicated staff member (1 FTE) to create, maintain and support the proposed climate database (MCD). This is an ambitious enterprise in itself and will require a dedicated staff member (in addition to data storage, database documentation and ample web resources) for this effort.

Implicit in the above staff structure are graduate and undergraduate student opportunities on a part-time basis. In addition, a dedicated MCMC postdoctoral

opportunity (the *James B. Pollack NPP Fellow*) within the NASA Postdoctoral Program will also augment the core staff of the MCMC.

In order to advise and guide the daily operations of the MCMC, a Director and Assistant Director of the facility will also be necessary. Such personnel would oversee the day-to-day operations and address, delegate and respond to, Agency-initiated and community requests for climate simulations, data acquisitions, etc.

For guidance on the general MCMC operations, facility maintenance and in planning of future directions, a Steering Committee will be established. Membership of this committee would come from both 1–2 central staff as well as the broader scientific and engineering communities (5–7) on a rotating basis with 3-year tenureships. The Steering Committee would provide general guidance on all the activities conducted at the MCMC (e.g., scientific, engineering and technical matters), and would report directly to the MCMC Director. Together with inputs from the broader community, the Steering Committee and Director would also set general guidelines for the MCMC's incorporation of new codes and modules, (both from within the MCMC and from the community).

Finally, an independent Advisory Board would be established that would have oversight of both the centralized MCMC and the actions of the Steering Committee. Membership would include representation from NASA HQ, MEP/MEPAG, the Mars climate and mission related community, and representation from high-end computing (HEC). The Advisory Board would conduct periodic thorough reviews and would report directly to NASA's PSD.

6.0 MCMC High-End Computing

Having a colocated NASA HEC resource (ARC's NAS facility) at the same NASA center as the MCMC has tremendous advantages in terms of computational and data storage capabilities.

This facility will permit very high-resolution simulations (e.g., equivalent sub-degree latitude-longitude resolutions) over many annual cycles to be performed. For example, improved modeling Mars' dust cycle requires dynamically resolving surface processes associated with dust lifting. It can also circumvent the need to highly parameterize some sub-grid physical processes that can be consistently resolved. In this way, the state-of-the-art global model will resolve phenomena that is typically only resolved in limited-area, regional-scale atmospheric models. To perform such high-resolution simulations, the computational demands would exceed those of individual researchers on typical single- and multi-processor workstations alone.

Another advantage will be to offer user accounts and requests under one common group. In addition to the standard NASA HEC accounts request and allocations procedure available from HEC e-Books (<https://ebooks.reisys.com>) open to all NASA R&A award recipients, it is envisioned that a large, dedicated block resource from NASA HEC — in particular from the NAS facility (Columbia/Pleiades) — would be assigned to the MCMC for both the local and remote (i.e., broader community) MCMC members. Such accounts and allocations would not be required to go through a separate e-Books system request (i.e., extra accounting and reporting steps in themselves which would be duplicative) but would be streamlined to go directly through the high-end computing asset block from the MCMC. Periodic utilization reviews of the entire MCMC user community regarding HEC requests, allocations, used CPU cycles and storage requirements would be conducted internally and then reported back to the NAS Division Chief and/or the NASA HQ Program Manager for HEC resources.

7.0 MCMC Community Interactions

Incorporating community feedback related to its experiences with MCMC codes and products is essential. It also mandates that the MCMC be flexible by design and adaptive to the changing needs of its users. This increases the overall return on the investment in the MCMC by NASA.

A method for regularly testing and ultimately integrating community-derived, externally-funded codes and other modeling inputs, is critical to the success of the MCMC. As a community resource, independently-developed routines and parameterizations that can improve the quality and state of Mars climate modeling need to be considered for inclusion as either options or default upgrades to the baseline codes available within the MCMC. MCMC staff will be prepared to work with members of the community to enable adherence to the coding practices of the center, perform careful testing, in order to gain the full functionality of new routines within a common modeling infrastructure.

Yet further, this interaction with the community will offer an effective “feedback loop” with regards to physical processes developed by separately-funded projects related to Mars climate science. It will also offer an incentive to “plug-and-play” with components of, and even utilize a full suite of climate codes available from, the MCMC. In this way, the robustness and sensitivity of *all* physical packages with relevance to the Mars climate system may be objectively assessed, and then, the climate modeling attributes of the MCMC will be enhanced both for the Agency and the community at large.

8.0 MCMC Reviews and Accountability

As described above in section 5, three separate tiers of direction and guidance will be established which will naturally provide a means for oversight, review and accountability of the MCMC. The first is via direct communications from the science and engineering communities to the MCMC Director. On the overall requirements for operations of the MCMC, this would be complemented via advice and guidance originating from the Steering Committee.

Upon approval of this White Paper by NASA Headquarters, the first course of action will be to create a detailed *Operational Plan and Budget* for the MCMC, which would be subject to Headquarters approval. Once operations begin, key milestones will need to be established that can objectively assess the functions, performance and overall responsiveness of the MCMC to the Agency's and the community's needs. Evaluation of such metrics will be gathered and presented to NASA Headquarters on a quarterly basis (e.g., via Quarterly and Annual Reports).

Full oversight reviews of all aspects of MCMC operations and functionality would occur triennially (e.g., in line with typical R&A proposal cycles) and would be conducted either onsite at ARC or at Headquarters through the overarching Advisory Board of the MCMC. As discussed above, the Advisory Board would be comprised of members of the broader MEP and HEC communities.

Finally, an important outcome of the triennial reviews would be to set any new directions and course changes for an *evolving* MCMC. On a basic level, the MCMC would be established with a fundamentally flexible and adaptive design. Based on changes in near-term and long-range future needs of the Agency and the broader Mars climate community, the MCMC will be well poised to accommodate changes. These include changes in its basic charter, its primary functions and activities, and scope of community interactions, which are in line with any new requirements (e.g., the development, testing/debugging, documentation and maintenance of climate models for other planetary atmospheres).

9.0 References

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10. Appendix A

The final agenda of the autumn 2008 MCMC workshop held at the NASA Ames Research Center, Moffett Field, CA, is listed below:

A list of all participants that registered and attended the MCMC workshop is given below: